LCA Case Studies

Life Cycle Assessment for the Implementation of Emission Control Measures for the Freight Traffic with Heavy Duty Vehicles in Germany

Phase 3: Life Cycle Interpretation *

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Abstract. This Life Cycle Interpretation Analysis describes the third phase of the Life Cycle Assessment (LCA) for the implementation of emission control measures for the freight traffic with heavy duty vehicles (HDV) in Germany. It is based on the December 1999 edition of ISO/DIS 14043. Special emphasis was placed on the determination of the ecological effectiveness and the ecological category indicator effectiveness for each emission control scenario to compare the overall ecological-economical effect of the emission control measures investigated. Following these steps the main factors influencing the Life Cycle Impact Assessment (LCIA) results were identified. As a result of these analyses only a small number of influencing factors were detected having an influence on the LCIA result of more than 93%. Another result was the determination of the main influence factors from the different phases of the Product Life Cycle (PLC) of the selective catalytic reduction (SCR) system on the total weighting results of the bulk environmental load. The influence of the Life Cycle Inventory Analysis (LCI) results on the final Category Indicator Effectiveness result was analysed. The contribution of the different phases of the PLC of SCR systems on the total result of the LCI with regard to the bulk environmental load was determined. A completeness and sensitivity check was carried out. The results of the study enable plausible conclusions and recommendations, the absolutely essential one being the introduction of an consumption-optimized Diesel engine with SCR systems by the reference year 2005 for ecological and economical reasons.

Keywords: Diesel engines; diesel fuel-based measures; engine-based measures; freight traffic; heavy duty vehicles; life cycle interpretation; nitrogen oxides; particulate trap; SCR catalysts; urea selective catalytic reduction process

Introduction

This analysis represents the third part of the LCA as per [1]. It is a continuation from the life cycle inventory (LCI) results and the LCIA published in [2] and [3]. This life cycle interpretation is the final phase of the life cycle assessment (LCA) and is based on the December 1998 edition of ISO/DIS 14043 (cf. [4]). Because the results of the mandatory and optional elements of the LCIA do not allow a clear conclusion to be drawn and establish no relationship to the economic effects of the corresponding scenarios, the ecological effectiveness and ecological category indicator effectiveness are determined for each scenario to allow a comparison of the available alternatives.

1 Identification of Significant Parameters

1.1 Ecological effectiveness and ecological category indicator effectiveness

Ecological effectiveness (EE), cf. [5]) establishes a relationship between the overall decrease or increase in environmental loading (R: results from LCIA, see [3]) which has been or could be achieved by implementing an environmental engineering process, product or method over the entire technical service life with the overall environmental protection costs (EPC, see [2]) which have resulted or will result. The higher the magnitude of EE, the more positively the alternative to be evaluated can be classified (Eq. 1).

$$EE = \frac{R}{EPC} \quad \text{in overall ecological relief units/DM} \qquad \text{Eq. 1}$$

EE can be negative as well as infinite. A negative EE is obtained if a negative reduction in load on the environment is achieved despite incurred environmental protection costs, i.e. if the corresponding measure is counterproductive. In this case the measure does not fulfill the intended environmental protection goals and must therefore be rejected. If no other alternatives are available and if geographical or environmental-category-oriented shifting of the load on the environment is declared as a goal despite the overall counterproductive nature of the planned measure, the following must then be interpreted separately as decision criteria:

1. Absolute magnitude of overall loading of the environment
2. Absolute magnitude of entire environmental protection costs.

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Table 1: Ecological effectiveness for the studied scenarios in comparison with the ecological effectiveness for the SCR process in the case of power station plants with SCR honeycombs in low dust operation (cf. [5])

Weighting methods	Low Dust	EU3M, 2010	V_1, 2010	V_2, 2010	V_2, SP, 2010	V_3, 2010 and V_3, SP, 2010	V_4, 2010
Ecoscarcity, Switzerland in ERP/DM	6,827	6,307	6,577	40,970	34,940	∞	986
Tellus U.S.A. in reduction of U.S. $ costs/DM	1.28	1.03	1.27	8.53	7.38	∞	0.24
EPS in reduction of ECU costs/DM	-0.02	-0.22	0.03	1.52	1.49	∞	-0.01
Effective category in reduction of short-term units/DM	619	473	620	4,226	3,655	∞	105
Effective category in reduction of long-term units/DM	587	212	581	4,453	3,914	∞	135
KQR in reduction of EPSU/DM	878	848	839	5.279	4,516	∞	117
Ecoscarcity, Norway in ERP/DM	1,419	1,084	1,434	9,779	8,446	∞	261
Ecoscarcity, Sweden in ERP/DM	698	384	714	4,948	4,248	∞	185

This approach is recommended, because at a given identical value of overall loading of the environment, the value of the EE approaches zero with increasing entire environmental protection costs and thus appears to be more 'positive', which can lead to false conclusions.

The EE can take on an infinite value if an environmental engineering measure achieves a reduction in both ecological and economic load (overall negative environmental protection costs). In this case is the entire environmental protection costs are assigned a value of 0 (zero) to establish a clear differentiation from the measures with negative reduction in load on the environment. This results in an infinite value for EE. If a decision must be made between two or more measures with infinite EE values, the following must be interpreted separately as decision criteria:

1. The results of the LCIA (absolute magnitude of entire reduction in load on the environment)
2. The economic decision method.

The absolute contribution of the corresponding measure to the entire reduction in load on the environment should be considered first in the decision because this is based primarily on the reduction in load on the environment and not on the absolute economic value of a measure. Because measures with an infinite EE indicate a reduction in economic load, the additional application of economic decision methods is recommended in this case for deciding between two measures with infinite EE and an approximately equally large magnitude for absolute reduction in load on the environment. Possible decision criteria in this case could be determined by application of static (ROI and amortization calculations) or dynamic investment decision methods (cash value, capital value, internal interest base and annuity method). Table 1 shows the values for EE with the various scenarios and evaluation procedures. The EE for scenario 3 (V_3, 2005 to 2010) is infinite. As an infinite value for EE was determined for only one variant in the investigations performed, application of further decision criteria becomes unnecessary.

Table 2: Category indicator effectiveness (CIEj) for the studied scenarios

Category indicator effectiveness	EU3M, 2010	V_1, 2010	V_2, 2010	V_2, SP, 2010	V_3, 2010 and V_3, SP, 2010	V_4, 2010
1. Resources						
Energy consumption in kWh/DM	-9.64E+00	-7.60E-01	5.11E+01	5.11E+01	∞	-1.17E+00
Material consumption in 1/DM	-2.03E-02	3.40E-05	1.19E-01	1.19E-01	∞	-2.47E-03
2. Water consumption in g/DM	-5.34E+03	7.93E+00	3.13E+04	3.13E+04	∞	-6.50E+02
3. Land use in ELU/DM	-1.09E-05	-6.63E-06	2.48E-05	2.48E-05	∞	-1.33E-06
4. Human toxicity in g body weight/DM	2.50E-03	1.36E-02	2.94E-01	2.94E-01	∞	2.45E-02
5. Global warming in g CO_2-eq/DM	-2.57E+03	-4.74E+01	1.46E+04	1.46E+04	∞	-3.11E+02
6. Stratospheric ozone depletion	n. c.	n. c.	n. c.	n. c.	n. c.	n. c.
7. Acidification in g SO_2-eq/DM	1.13E+02	1.08E+02	6.64E+02	5.64E+02	∞	1.54E+01
8. Eutrophication in g PO_4-eq/DM	-7.27E-04	-8.58E-05	3.73E-03	3.73E-03	∞	-8.85E-05
9. Summer smog in g ozone/DM	2.78E+01	1.74E+02	1.06E+03	9.02E+02	∞	7.02E+01
10. Ecotoxicity in t DBM/DM	-3.20E-01	6.99E-02	2.16E+00	2.16E+00	∞	3.24E-01
11. Radiation in Bq/DM	-8.19E+01	0.00E+00	4.79E+02	4.79E+02	∞	-9.96E+00
11. Radiation in man-Sv/(a*DM)	-2.06E-12	0.00E+00	1.20E-11	1.20E-11	∞	-2.50E-13
12. Noise nuisance	n. c.	n. c.	n. c.	n. c.	n. c.	n. c.
13. Waste in ERP/DM	-6.84E-01	-2.58E-02	3.84E+00	3.84E+00	∞	-8.32E-02

Analogous to the EE, category indicator effectiveness values (CIE) are generated for evaluating the results of the characterization stage (**Equation 2**).

$$CIE_j = \frac{CIR_j}{EPC} \quad \text{in category endpoint/DM} \qquad \text{Eq. 2}$$

The CIE_j for a category indicator j (see **Table 2**) establishes a relationship between the overall indicator value for an impact category j (CIR = category indicator result) and the entire environmental protection costs (EPC) incurred by application of an environmental engineering process, product or method over its entire technical service life. The CIE_j decision making process is identical to EE decision making process . As was the case for EE, scenario 3 (V_3, 2005 to 2010) also has an infinite CIE_j.

1.2 Significant factors influencing the result of the LCIA

The following rating criteria from [4] are applied for the interpretation:

- A: Highest importance, significant influence, i.e. contribution >50%
- B: Very important, relevant influence, i.e. 50% ≥ contribution >25%
- C: Moderately important, some influence, i.e. 25% ≥ contribution >10%
- D: Less important, slight influence, i.e. 10% ≥ contribution >2.5%
- E: Unimportant, negligible influence, i.e. contribution <2.5%.

In order to ensure clear presentation of the most important influencing factors on the bulk environmental load from the PLC of the SCR systems, only a small number of influencing factors was selected which determined the overall result by more than 93% for all applied weighting methods (**Table 3**). The relevant to significant influence of NH_3 emissions in most of the weighting methods and of CO_2 emissions in the EPS method on the overall result is thus clearly identifiable.

The most important influencing factors on the bulk ecological relief for variant 3 (V_3, 2010) are given in **Table 4**. It can be clearly seen that only five environmental effects have a decisive influence of more than 98% on the weighting result. Based on this, in nearly all of the weighting methods (with the exception of the EPS method with CO_2 reduction) NO_x reduction can be assigned the highest importance for the overall result of the bulk ecological relief.

Table 3: The main influencing factors on the weighting result of the bulk environment load through the PLC of the SCR systems for the variant 3 (V_3, 2010) according to the applied weighting methods

Weighting method	Ecoscarcity, Switzerland	Tellus	EPS	Effect category, short-term	Effect category, long-term	KQR	Ecoscarcity, Norway	Ecoscarcity, Sweden
Thermal energy consumption	D	E	E	B	B	E	D	D
NO_x (as NO_2)	D	D	E	D	E	B	E	E
NH_3	A	B	D	B	B	C	B	A
SO_2	D	C	E	E	E	B	D	E
CO_2	E	C	B	D	D	E	D	E
CO_2-eq	E	D	B	D	D	E	D	E
CH_4	E	E	D	E	E	E	D	D
NMVOC	D	D	D	D	D	E	D	D
Iron in waste water	E	E	E	E	E	D	E	E
Waste, land farming	E	E	E	E	E	E	B	E
Total	99.03%	94.61%	98.35%	93.27%	93.96%	96.13%	96.08%	98.24%

Table 4: Main influencing factors on the weighting results of the bulk ecological relief through the PLC of the SCR systems for the variant 3 (V_3, 2010) in accordance with the applied weighting methods

Hazardous material	Ecoscarcity, Switzerland	Tellus	EPS	Effect category, short-term	Effect category, long-term	KQR	Ecoscarcity, Norway	Ecoscarcity, Sweden
Thermal Energy consumption	E	E	E	D	D	E	E	D
NO_x (as NO_2)	A	A	C	A	A	A	A	A
SO_2	E	E	E	E	E	E	E	E
CO_2	E	D	A	E	C	E	D	D
NMVOC	E	E	E	E	E	E	E	D
Particles	E	D	E	E	E	E	E	E
Total	99.75%	99.77%	99.67%	99.65%	99.46%	97.76%	98.52%	99.53%

Table 5: Influence of the different phases of the PLC of the SCR systems on the total weighting results of the bulk environmental load in the case of the variant 3 (V_3, 2010)

PLC phase	Ecoscarcity, Switzerland	Tellus	EPS	Effect category, short-term	Effect category, long-term	KQR	Ecoscarcity, Norway	Ecoscarcity, Sweden
Production, direct	E	E	E	E	E	E	E	E
Production, secondary	E	D	D	E	E	D	D	E
Input material, direct	E	D	D	E	E	C	E	E
Input material, secondary	D	D	D	D	D	C	C	E
SCR system, direct	A	B	D	B	B	C	B	A
SCR system, secondary	C	B	A	B	A	B	B	C
Recycling, direct	E	E	E	E	E	E	E	E
Recycling, secondary	E	E	E	E	E	D	D	E
Total	100%	100%	100%	100%	100%	100%	100%	100%

Table 5 shows the influence of various phases of the PLC of the SCR systems on the overall weighting result for variant 3 (V_3, 2010) relative to the bulk environmental load. The particularly significant influence during the implementation phase of the SCR systems on the result of the bulk environmental load can be clearly seen in this table. It applies for all of the application variants of SCR systems investigated in this study.

The most important influencing factors on the category endpoints for all scenarios are given in Table 6.

Table 6: Influence of the life cycle inventory analysis results on the final category indicator results

Category indicator	Actual, 1995	K, 2010	K+EU3M, 2010	V_1, 2010	V_2, 2010	V_3, SP, 2010	V_3, 2010	V_4, SP, 2010	V_4, 2010
1.1 Energy consumption									
Thermal in MJ	A	A	A	A	A	A	A	A	A
1.2 Material consumption									
Raw oil use in t	A	A	A	E	A	A	A	A	A
Fuel mix FRG (fossil) in kg	D	D	D	E	D	D	D	D	D
TiO_2 in kg	E	E	E	B	E	E	E	E	E
WO_3 in kg	E	E	E	D	E	E	E	E	E
FeS_2 in kg	E	E	E	A	E	E	E	E	E
2. Water consumption									
Process water in g	D	D	D	A	D	D	D	D	D
Cooling water in g	A	A	A	E	A	A	A	A	A
Cleaning in g	E	E	E	C	E	E	E	E	E
3. Land use									
Land use in m^2	A	A	A	A	A	A	A	A	A
4. Human toxicity									
CO in g	E	E	C	E	E	E	E	E	E
Particulate matter in g	A	A	A	A	A	A	A	A	A
5. Global warming									
CO_2 in g	A	A	A	A	A	A	A	A	A
CO_2eq in g	E	E	E	B	E	E	E	E	E
7. Acidification									
SO_2 in g	C	D	E	E	E	E	D	D	D
NO_2 in g	A	A	A	A	A	A	A	A	A
8. Eutrophication									
Ammonium in g	B	B	B	A	B	B	B	B	B
COB in g	A	A	A	E	A	A	A	A	A
9. Summer smog									
NO_2 in g	A	A	A	A	A	A	A	B	B
NMVOC in g	B	D	B	D	D	D	B	A	A
10. Ecotoxicity									
Aromatic hydrocarbons in g	C	B	C	D	C	C	C	C	D
CO in g	B	B	A	D	D	D	B	B	A
Particulate matter in g	A	B	D	A	A	A	A	A	B
11. Radiation									
Noble gases in Bq	C	C	C	E	C	C	C	C	C
Tritium in Bq	C	C	C	E	C	C	C	C	C
Ball resin in Bq	B	B	B	E	B	B	B	B	B
Evaporator concentrate in Bq	C	C	C	E	C	C	C	C	C
13. Waste									
Residue material dump in g	D	D	D	B	E	E	E	E	E
Ash in g	A	A	A	E	A	A	A	A	A
Boiling wastes to MVA in g	E	E	E	B	E	E	E	E	E

The endpoints of the impact category for generation of photooxidants in variant V_4 are discussed below. For this variant, the NMVOC results from the inventory analysis assume the highest importance in the overall result of this impact category, with 84% for reference year 2005 and 70% for reference year 2010. This special aspect of variant V_4 is due to the fact that the introduction of EC1 diesel fuel was assumed for this variant. By application of specified specific reactivity (SR for fuel C from [6]) for evaluation of NMVOC emissions in exhaust gases from EC1 diesel fuel for variant V_4 with SR = 4.12 mg ozone/mg NMVOC instead of SR = 5.01 mg ozone/mg NMVOC as for the other scenarios it is possible to achieve a pronounced short-term effect which decreases over the long term. The reductions in NMVOC emissions achieved with variant V_4 were also evaluated in comparison with the reference scenario with SR = 5.01 mg ozone/mg NMVOC. The influence of the NO_x results of the LCI on the category indicator result for summer smog decreases to 16% over the short term and then increases again to 30%.

With regard to the impact category for ionizing radiation, scenario V_1 did not reveal any influences because this measure exhibits neutral behavior in terms of fuel consumption and the influences on this impact category arise specifically from the diesel fuel manufacturing process.

An extensive presentation of the influences of direct and secondary environmental effects on the overall LCI results for all scenarios would exceed the scope of this publication, and this paper therefore only addresses the most important influencing factors and special aspects. For the scenarios 1995, introduction of fuel-side, engine-side and exhaust-gas side measures (variant V_4), nearly all LCI results are influenced 100% by the secondary environmental effects. These secondary environmental effects arise in the diesel fuel manufacturing process. This statement does not hold for the LCI results regarding thermal energy consumption, flue gas volume, CO_2, CO, SO_2, NO_2, CH_4, NMVOC or particulate matter emissions. For the 1995 scenario, the fraction of direct environmental effects in the overall LCI result is 67% for CH_4 and 54% for SO_2. For the scenarios introduction of fuel-side and engine-side measures, the influence of secondary environmental effects on the overall LCI result increases to 75% for SO_2 and to 83% for variant V_4. In the scenarios introduction of fuel-side measures and V_4, the influence of secondary environmental effects on the overall LCI result also increases to 84 or 71% for CH_4. In the scenario introduction of engine-side measures, the fractions of direct and secondary environmental effects in the overall LCI result are each 50% for CH_4. Also of interest is the development of LCI results of NMVOC for the scenarios introduction of fuel-side and engine-side measures and variant V_4. The influence of secondary environmental effects on overall LCI result increases from 7% to 44, 13 and 27% respectively. For the remaining analysis results, these values are determined by more than 93% by direct environmental effects. For variants V_1, V_2 and V_3 for introduction of exhaust-gas side measures, the distribution of influences of direct and secondary environmental effects on the overall LCI result principally agrees with the results presented above. Certain differences arise in the allocation of secondary environmental effects to the manufacturing processes for diesel fuel, SCR systems and auxiliary process materials. This procedure enables consideration of a series of environmental effects, which could not be covered or which were not relevant for the diesel fuel manufacturing process, from the PLC of SCR systems for these variants (**Table 7**).

Table 7: Contribution of the different phases of the PLC of the SCR systems on the total result of the life cycle inventory analysis with regards to the bulk environment load for the most important effects on to the environment in the case of variant 3 (V_3, 2010)

PLC phase	Prod.	Prod.	Preprod.	Preprod.	SCR	SCR	Disposal	Disposal	Total
Hazardous material	direct	second.	direct	second.	direct	second.	direct	second.	Total
Air emissions:									
NH_3	E	E	E	E	A	E	E	E	100.00%
HCN	E	E	E	A	E	E	E	E	100.00%
MEA	A	E	E	E	E	E	E	E	100.00%
H_2S	E	E	E	A	E	E	E	E	100.00%
Waste water contamination:									
Sulfate	E	E	A	E	E	E	E	E	100.00%
NO_3	A	D	E	E	E	E	E	E	100.00%
Phosphate	A	E	E	E	E	E	E	E	100.00%
Iron	E	E	A	E	E	E	E	E	100.00%
Titanium	A	E	E	E	E	E	E	E	100.00%
Vanadium	B	E	A	E	E	E	E	E	100.00%
Tungsten	A	E	E	E	E	E	E	E	100.00%
Zinc	E	E	E	A	E	D	E	E	100.00%
Waste:									
Recycling	A	E	E	E	E	E	D	E	100.00%
Reutilization	C	E	E	E	E	E	A	E	100.00%

2 Evaluation

2.1 Completeness check

For the category indicator for resource/materials use, the overall contribution of TiO_2, WO_3, V_2O_5 and FeS_2 from the PLCs of SCR catalysts is of absolute importance in variant V_1, as use of these raw and input materials makes up 100% of the sum of the category endpoints. The individual contributions to the overall sum of the category endpoints must be rated as follows:

- FeS_2: Contribution is form highest importance (53.3%)
- TiO_2: Contribution is very important (39.2%)
- WO_3: Contribution is less important (4.5%)
- V_2O_5: Contribution is less important (3.0%).

For all other measures where these LCI results were considered and evaluated, they make up less than 2.5% of the entire sum of category indicator results for this impact category. They can therefore be rated as unimportant. The LCI results for TiO_2, WO_3, V_2O_5 and FeS_2 are irrelevant for the measures without SCR systems. In this context, the investigation should concentrate on other main points such as use of noble metals for particulate traps. However, this must be performed with primary data from the system manufacturers, and these data were not available. Estimates are unsuitable for this purpose because these measures do not lead to fuel savings but rather to increased fuel consumption. For the category indicator for water use, the LCI results for cleaning and drinking water were considered only for SCR catalyst manufacture. The contribution from the LCI result for cleaning water can be rated as only of moderate importance for variant V_1. The consumption of cleaning water is determined particularly by interruptions in the process with subsequent cleaning of the machinery and equipment. These interruptions primarily depend on the order situation and the type of lots used (raw materials composition) and are therefore subject not only to technical fluctuations but also market-induced fluctuations. The influence of the LCI result for drinking water can be rated as less important to negligible. In the LCI result for CO_2 equivalents, emissions of greenhouse gases from the PLC of the SCR systems were summarized by their evaluation with the corresponding values for their greenhouse potential over a period of 100 years. These values are therefore not presented in this form for the measures without SCR systems. In this case the values were not summarized until after the characterization stage. For the category indicators for air emissions of H_2S and HCN as well as water emissions of titanium, vanadium, tungsten and zinc complexes, data could be obtained only for the PLC of the SCR systems. It can be seen in [2] that these LCI results are negligible for the category endpoints for ecotoxicology in scenarios V_1 to V_3. For the LCI result for water emissions of iron complexes, data could be obtained only for the PLC of the SCR systems. The contributions of these LCI results to the above category endpoints can be rated as unimportant (V_3 and V_2) to less important (V_1). For the impact category for eutrophication, data on the LCI results for water emissions of nitrates and phosphates could be obtained only for the PLC of the SCR systems. In accordance with the rating criteria, these make a negligible contribution to the overall result of the eutrophication impact category during scenario V_1, with 9.4% for nitrates and 7.8% for phosphates. This contribution decreases to -0.7 to -1.3% for scenarios V_2 and V_3 for both category indicators and can thus be rated as having a negligible influence.

Analysis of **Appendix 1** from [2] in conjunction with **Appendix 1 from** [3] provides an extensive overview of the significance of the data from the LCI results which were not evaluated. The following four LCI results could not be evaluated:

- Air emissions of monoethanoamine (MEA)
- Oil content in wastewater
- Emissions of substances which can be sedimented in wastewater
- Emissions of sodium ions in wastewater.

Appendix 1 (see [2] **and** [3]) shows that all of these LCI results were assigned to the ecotoxicology impact category and that they are lower than the air emissions of particles by factors 10^2 to 10^4. This means that these LCI results could have an influence on the result of the impact category only if their ecotoxicity were evaluated as higher by these same factors than that for the LCI result for air emissions of particles. There is no reason for this at present.

As there are currently no scientifically founded factors for weighting the category indicator results, the LCI results were weighted using several quantitative evaluation methods. All of the applied methods exhibit gaps in the weighting factors.

2.2 Sensitivity check

The first part of the sensitivity check was already performed during the data collection and analyses. By strict division of the environmental effects into direct and secondary effects, it was then possible to demonstrate their influence on the overall LCI results. This made clear that a very large number of the traffic-induced environmental effects are secondary effects which arise during the diesel fuel manufacturing process and are thus directly proportional to fuel consumption. The influences of measures which target not only a reduction in direct emissions but also a reduction in fuel consumption become clear when comparing the results for variant V_1 with those for variant V_2 in **Appendix 1** (cf. [2]). In addition, the influences of the various phases of the PLC for the SCR systems on the overall result of the bulk environmental load are determined from the inventory analysis, and the most important influences are presented in **Table 7**. It was assumed for the sensitivity check that a 15% reduction in the overall conversion of nitrogen oxides and hydrocarbons achievable and confirmed by experimental results is obtained in scenarios V_2 and V_3 with unchanged consumption of reducing agent (urea). The results of the sensitivity check are given in **Appendix 1** (cf. [2] and [3]) and in **Tables 1 - 2**.

3 Conclusions

For both the ecological category indicator effectiveness for all impact categories (CIE_j) as well as for ecological effectiveness (EE), variant V_3 is the best alternative for all weighting methods. Variant V_2 clearly took second place. These results were confirmed by the sensitivity check. In addition, the completeness check also revealed that the most complete data basis could be obtained for variants V_1 to V_3. It

was further demonstrated that the data not acquired at all for several variants have either a negligible or only slight influence on the overall result. In addition, the data gaps in the applied characterization factors are very slight and only comprise a total of four secondary environmental effects from the entire inventory analysis. It can therefore be anticipated that a later evaluation of these environmental effects will not change the overall result for the affected category endpoint and for the LCIA. With regard to the currently existing gaps in the weighting for all available quantitative methods, various methods were applied in an attempt to determine the effects of the design-related advantages and disadvantages of these methods on the overall result. As only the absolute magnitude of the overall result changed and the trend was clearly confirmed for the ecological effectiveness with all applied methods, and also after performance of the sensitivity check, no fundamental changes in the overall result are anticipated in this case due to the existing gaps in the weighting. In this case the result for the ecological category indicator effectiveness serves as a basis for comparison. Considering the objectives specified in [2], variants V_3 and V_2 are thus the best alternatives for selection. The main difference between these two measures lies in the time of implementation. This changes not only the composition but also the assumed technical standards of the vehicle pool and the valid technical standard for the reference scenario. For variant V_2, the reference scenario includes the fuel-side measures and the technical standard up to EURO 2. Variant V_3 accounts for the introduction of EURO 3 (with engine-side measures) starting from the year 2000 with the associated advantages and disadvantages. By accounting for the results of the introduction of EURO 3 it becomes clear that variant V_3 profits especially from the negative direct and secondary environmental effects as well as from increasing environmental protection costs which result from the introduction of EURO 3. This yields not only a true decrease in ecological load, but also a decrease in economic load following a prior increased economic load. The interaction of both factors in determining ecological effectiveness (EE) and ecological category indicator effectiveness (CIE_j) means that the evaluation rates V_3 as the best measure. Variant V_2 (consumption-optimized diesel engine with SCR-system up to year 2000) should be given preference in order to prevent both the negative ecological and economic influences from the introduction of EURO 3 instead of later compensating them again by introducing variant V_3, a well as to realize the highest potential for emissions reduction up to 2010. However, implementation of this scenario by the anticipated starting time (2000) is not realistic because of political decisions. The introduction of variant V_3 (consumption-optimized diesel engine with SCR-system) by reference year 2005 should therefore be regarded as absolutely essential from an ecological and economic standpoint.

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The Life cycle inventory analysis (LCI) for the freight traffic with heavy duty vehicles in Germany was determined for the reference year 1995 and the target year 2010 by application of ISO 14040 and ISO 14041. Based on these results and under consideration of the dynamic development of road freight traffic with German heavy duty vehicles of >14 t max laden weight and composition of the German heavy duty vehicles fleet in this class the LCI for the introduction of various scenarios for reducing emissions from freight traffic was generated. Special emphasis was placed in the determination of the LCI for the implementation of primary, secondary and a combination of primary and secondary emission reduction measures for heavy duty diesel engines such as variation of diesel fuel characteristics, engine-based measures for exhaust gas optimisation, urea selective catalytic reduction (SCR) process with and without fuel consumption optimised diesel engines and particulate trap for exhaust gas optimised diesel engines with low sulphur diesel fuel. The overall environmental effects of the investigated measures on the other phases of the product life cycle of the freight traffic with heavy duty vehicles and on associated and new products to be introduced was included in the generated results for the LCI of each variant. For the implementation of the urea SCR process the results are based on manufacturer data for the overall production process of SCR honeycomb catalysts and SCR application measurements in engine and field test after a travelled distance of between 187,825 and 325,178 km under road traffic conditions with typical EURO 2 standard diesel engines for heavy duty vehicles with a max laden weight of >32 t under control of and data certification by TÜV Automotive Bayern Sachsen GmbH.

Phase 2: Life Cycle Impact Assessment
Int J LCA 6 (5) 285–292 (2001)

Under consideration of the overall Life Cycle Inventory Analysis (LCI) results generated in the first step of this study and based on the February 1999 edition of ISO/DIS 14042 the Life Cycle Impact Assessment (LCIA) for the introduction of various emission control measures for freight traffic heavy duty vehicles in Germany was determined. For the examination of the several mandatory elements 11 impact categories related to the freight traffic and the LCI results were focussed, the LCI results were designed to these impact categories and with characterization factors of the 11 selected and recognized characterisation models the categories indicator endpoints were quantified. The optional elements for normalization and weighting were added to the analysis. Two reference values are used for normalizing the category indicator results. For the weighting step 8 recognized evaluation methods were selected with the aim to aggregate the LCI results to an overall value. The results enable plausible conclusions with regard to the ecological advantages and disadvantages of the use of each analysed emission control technology for heavy duty diesel vehicles. As no perfectly clear ranking can be distinguished for evaluation of the generated results and no correlation can be established to the economical effects of the corresponding measurements, it is necessary to complete the currently existing recommendation from the ISO/DIS-Standards with further parameters.